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## Dynamic performance evaluation of the HelioTrough® collector demonstration loop – towards a new benchmark in parabolic trough qualification

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### Abstract

The HelioTrough collector developed in industry-research cooperation is a parabolic trough collector with significantly increased aperture width and length. At the end of 2009, HelioTrough collectors were installed and have been continuously operated in the SEGS-V field at Kramer Junction (California, USA) for testing and demonstration purposes since then. The evaluation of thermal collector performance is based on measurement equipment installed in the test loop, in particular flow meters, temperature sensors, and tracked pyrheliometers. Two kinds of performance analysis are carried out: A standard energy balance evaluation identifies and analyses periods of steady-state operation from a full range of field measurement data and delivers collector efficiency data for specific operating conditions. The advanced evaluation based on dynamic models delivers performance equation parameters and their uncertainties, and allows using more test data, also from non-steady-state test periods according to an advanced test method for solar field performance. The evaluation of the thermal test data includes a thorough analysis of the measurement equipment and a detailed uncertainty analysis for rating the test equipment and resulting data quality. The test results show the successful application of the advanced test and evaluation method and prove the high performance parameters of the HelioTrough (optical efficiency 0.816, thermal efficiency > 75% at nominal operating conditions). This transfer from pilot scale measurements to bankable performance parameters may serve as benchmark for the up-coming large-scale CSP projects.

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## 1. Introduction

A new parabolic trough collector development has two major objectives: cost reduction and proven performance increase compared to the state of the art. The installation and operation of a new type of collector in a demonstration loop concludes the collector development phase by finally proving its operability, reliability and overall performance. At the same time, it constitutes the first opportunity to obtain valuable performance data of a new design's full-size collectors under actual operation conditions in a power plant environment. On the basis of this data, performance parameters can be identified or verified and performance models and their predictions confirmed.

In contrast to the approach for solar field acceptance proposed by NREL [1] comparing thermal efficiency under static operating conditions, this method aims at identification of model parameters for field collectors from regular operation data. By its very nature, performance data obtained from (demonstration) loops are dynamic due to irradiance, sun angle, morning heat-up, night cool down and passing clouds. Thus, state of the art steady-state performance analysis reaches its limits: Either the data base has to be reduced to test sequences fulfilling quasi steady-state conditions - which represent only a small fraction of the available data and actual operation - or dynamic models and methods are required. One such dynamic model and method [4,5] has been developed at DLR and applied to performance data obtained at the demonstration loop of Flugsol's HelioTrough collector.

## 2. HelioTrough and its demonstration loop

The HelioTrough is a large novel parabolic trough collector based on a torque tube design with a focal length of 1.71 m, aperture width of 6.77 m and absorber tube diameter of 89 mm. One solar collector assembly (SCA) consists of 10 modules, (solar collector elements, SCE) adding up to a total length of 190 m [2, 3].

### 2.1. Test loop installation

The HelioTrough demonstration loop (Figure 1) is integrated in the SEGS-V power plant at Kramer Junction, California. Situated in the south-western part of the solar field, it replaced an old LS-2 loop (two rows of 400 m) and is operated as regular part of the solar field if no particular tests are scheduled.

The demonstration loop comprises two rows of HelioTrough collectors, consisting of two full-size collectors of 190 m each, and five shorter units for special purpose testing of mechanical parts. The aperture area of one full-size collectors is 1263 m<sup>2</sup>. Operation and intensive testing of the HelioTrough demonstration loop at Kramer Junction started in December 2009.

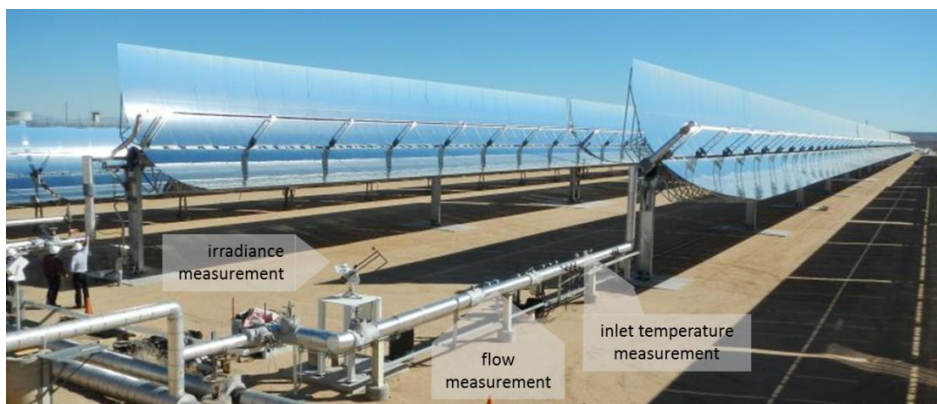


Figure 1. HelioTrough demonstration loop at Kramer Junction and installed performance test equipment.

## 2.2. Measurement configuration

As illustrated in Figure 2 the demonstration loop is equipped with measurement instrumentation consisting of two vortex flow meters installed at the loop inlet and 24 temperature sensors (pipe immersed RTD's with signal transmitters) measuring inlet and outlet fluid temperature of each collector. Three temperature sensors per measurement location increase the measurement quality. All sensors and transmitters were calibrated prior to installation.

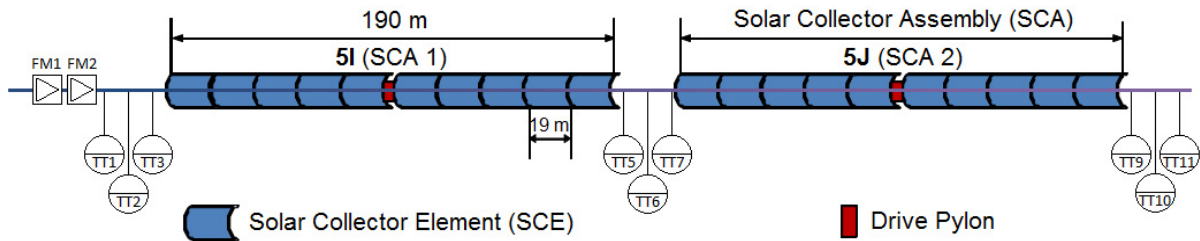


Figure 2. Performance test instrumentation at HelioTrough demonstration loop (first row)

A meteo station is installed in the direct vicinity of the loop and equipped with two pyranometers (one shaded) measuring global horizontal and diffuse horizontal irradiation as well as a pyrhelimeter of type CHP1 measuring direct normal irradiance ( $E_b$ ). The pyrhelimeter was calibrated prior to installation and recalibrated after the test period to investigate the sensor long-term drift, which turned out to be negligible. The records of ambient conditions are complemented by measurements of ambient temperature as well as wind speed and wind direction installed on a measuring mast. The cleanliness of the demonstration loop collectors is monitored recurrently every few days by reflectance measurements of the concentrator mirrors at multiple spots throughout the demonstration loop and averaging the results of all measurements. The cleanliness of the loop was between 93 and 98% during the evaluated test period. The measurement configuration, instruments and calibrations have been thoroughly reviewed and details enhanced by the DLR team. Furthermore, optical and mechanical tests completing the qualification of the demonstration loop were carried out in 2012.

## 2.3. Data base

For the purpose of this study, 21 operational days from mid-2011 to mid-2012 are selected from an extended testing phase between 2010 and 2013. In order to obtain results representative for collectors as used in future commercial projects, the full length collectors (situated in row 5) are analyzed. In the following, the performance test result for the first collector corresponding to the current design with roller bearings are presented and discussed. The operation conditions (flow rate, limited temperature range) result from its position at the inlet of the loop.

## 2.4. Test uncertainty

A thorough uncertainty analysis of the demonstration loop test configuration according to GUM [6] considering the uncertainty effects as listed in Table 1 for individual measurands results in combined measurement uncertainties ranging from  $\pm 2.1$  to  $\pm 7.9$  percentage points of collector efficiency ( $2\sigma$  or 95% confidence). Furthermore, this analysis reveals that uncertainty budgets are dominated by instrument uncertainties such as stability, temperature drifts and, in case of the pyrhelimeter, calibration uncertainty, while the repeatability of the test results is high. Particularly high values of test uncertainty - and thus unfavorable test conditions - arise from high ambient temperatures (transmitter temperature drift) and increasing time spans between sensor calibration and measurement. [7]

Table 1. Uncertainty effects considered for the HelioTrough demoloop test uncertainty budget

	$T_{in}$	$T_{out}$	$\dot{V}$	$\rho_{HTF}$	$c_p$	$\chi$	$E_b$
Calibration Uncertainty	x	x	x				x
Stability	x	x					
Temperature drift	x	x	x				x
Hysteresis	x	x					
Repeatability	x	x	x			x	x
Resolution (data logger)	x	x	x			x	x
Measurement. Uncertainty. (data logger)	x	x	x			x	x
Calculation				x	x		
Cleanliness						x	x
Linearity							x

### 3. Data evaluation

The collector heat gain is calculated from measurements of HTF mass or volumetric flow rate ( $\dot{m} = \rho \cdot \dot{V}$ ) and temperature using

$$\dot{Q}_{use} = \dot{m} \cdot c_p(T_m) \cdot \Delta T \quad (1)$$

where  $c_p$  is the average HTF heat capacity for the temperature range,  $\Delta T$  the temperature difference between collector inlet and outlet. The heat gain in relation to the effective irradiated solar power (calculated from collector aperture area  $A_{Apert}$ , direct normal irradiance  $E_b$ , cleanliness of mirrors  $\chi$ , and angle of incidence  $\theta$ ) describes the system efficiency as a function of measurable quantities:

$$\eta_{coll} = \frac{\dot{Q}_{use}}{A_{Apert} \cdot E_b \cdot \chi^{\frac{3}{2}} \cdot \cos(\theta)} \quad (2)$$

Using an exponent of 3/2 to cleanliness assumes similar soiling of mirrors and receiver glass envelopes thus, three passes of light through soiled surfaces are required compared to two in reflectance measurements.

Furthermore, collector performance can be modeled using an equation that comprises terms with parameters describing optical effects such as the optical efficiency  $\eta_{opt}$ , incident angle modifier  $\kappa$ , and thermal loss ( $c_1, c_2$ ). The last term  $c_5$  describes the thermal capacity of the system and is used in dynamic investigations only.  $\Delta T$  is the temperature difference between average fluid temperature  $T_m$  and ambient.

$$\frac{\dot{Q}_{use}}{A_{Apert}} = \eta_{opt} \cdot E_b \cdot \chi^{\frac{3}{2}} \cdot \cos(\theta) \cdot \kappa(\theta) - c_1 \cdot \Delta T_m - c_2 \cdot \Delta T_m^2 - c_5 \cdot \frac{\delta T}{\delta t} \quad (3)$$

The optical efficiency includes all contributing (optical) effects (reflection, absorption, geometries, etc.) for a clean system at normal incidence.  $\kappa(\theta)$  describes the incident angle dependency of the collector efficiency referred to as IAM and might be substituted by the parameter equation

$$\kappa(\theta) = 1 - a_1 \cdot |\theta| - a_2 \cdot \theta^2 \quad (4)$$

Being a characteristic feature of (single axis tracking) line focusing systems, cosine loss is included in eq. 3 rather than with the IAM. Both equations 3 and 4 represent accepted empirical approaches that have qualified for reproducing overall performance of parabolic troughs without attempting to model individual heat transfer mechanisms.

### 3.1. Steady-state performance analysis

In order to identify and analyze operational periods which fulfill quasi steady-state conditions the data base is filtered. Table 2 lists the main criteria to be met during a time span of 10 minutes.

The choice of filter criteria depends on the inherent operational behavior of the loop and may not be made too strict so that sufficient data remains. However, the application of rather soft filter criteria results in spreading of the remaining performance data. As long as spreading occurs equally in positive and negative direction it does not significantly influence the outcome of fitted results. The criteria differ from EN 12975-2 and are specific for this test.

Table 2. Filter criteria for steady-state conditions (to be met within 10 minutes steady-state period)

Criterion	min	max	variation
Volumetric flow rate $\dot{V}$	10m <sup>3</sup> /h	–	<10%
Inlet temperature $T_{in}$	200°C	400°C	<2°C
Outlet temperature $T_{out}$	200°C	400°C	<2°C
DNI $E_b$	700W/m <sup>2</sup>	–	<20W/m <sup>2</sup>

Figure 3 displays measured collector efficiency data (fulfilling steady-state operating conditions) at operating temperature (approx. 200-250°C) of all test days versus the incident angle. The dependence of the efficiency on the incident angle is clearly visible and can be expressed by the fitted regression curve. The corresponding identified IAM parameters are listed in Table 3.

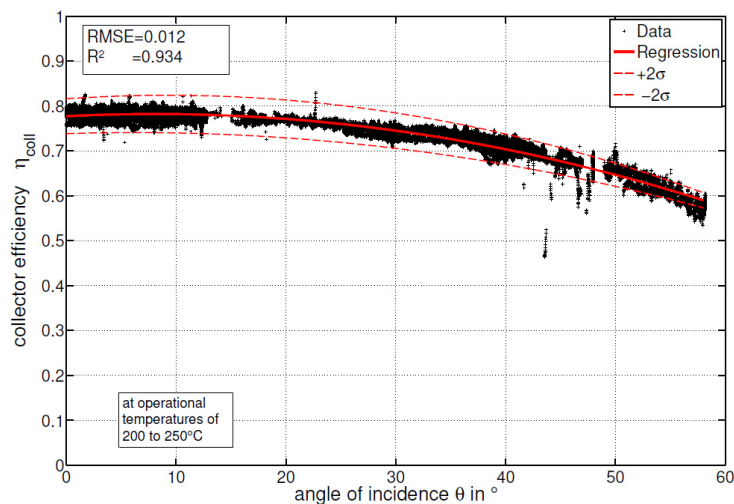


Figure 3. Steady-state thermal collector efficiency at 200-250°C mean HTF temperature versus incident angle and fit curve with 2σ uncertainty bands

Table 3. HelioTrough performance parameters resulting from steady-state data analysis of data collected at Kramer Junction demonstration loop.

Performance Parameter	value	uncertainty k=2 95% confidence	units
Peak efficiency*)	0.777	± 0.039	–
IAM $a_1$	-1.60·10 <sup>-3</sup>	± 0.53·10 <sup>-3</sup>	1/°
IAM $a_2$	9.90·10 <sup>-5</sup>	± 1.41·10 <sup>-5</sup>	(1/°) <sup>2</sup>

\*) optical efficiency at operating temperature (heat losses included)

As there is only little variation in operational temperature in a temperature controlled solar field loop in steady-state operation, temperature dependency and thus heat loss performance parameters of the collector efficiency cannot be determined reliably. This would only be possible by altering the solar field/loop operation or additional test measurements, thus interfering with regular operating conditions. [7]

### 3.2. Dynamic performance analysis

For the analysis of full-day collector performance data a dynamic solar field model is used [4]. This parameterized performance model combines classical collector performance modeling approaches in terms of optical efficiency, incident angle modifier and thermal losses with effects of pipe residence time and mixing, shading of neighboring rows and the focusing state of the system. Pipe geometry, heat transfer fluids and field/loop layout are fixed inputs to the model. Performance parameters and their respective uncertainties are determined from test data by means of numerical least squares optimization of the characteristics of useful heat on test days using a Levenberg-Marquardt algorithm. To this end, test periods valid for parameter identification are flagged in a preprocessing step. Performance parameter uncertainties are calculated combining random and systematic effects according to the ATM method [4]. Figure 4 shows how closely the parameterized dynamic performance model matches the measured collector performance on two exemplary test days.

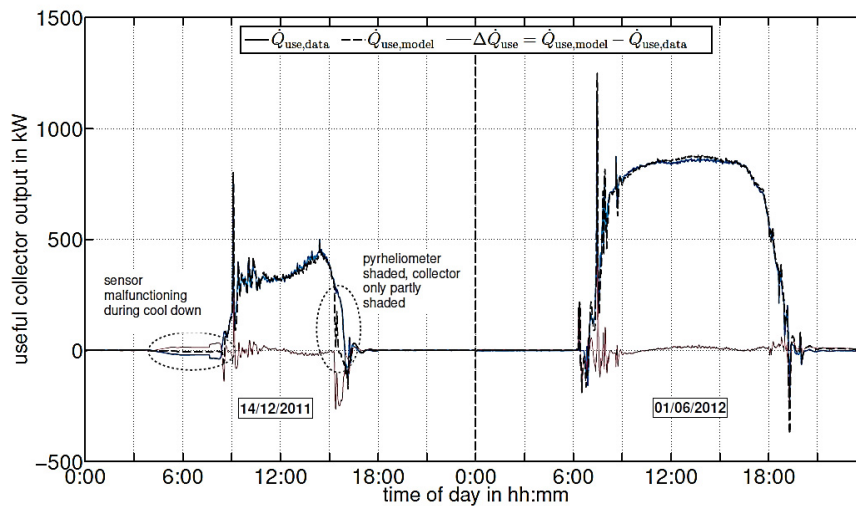


Figure 4. Agreement of measured and modelled dynamic collector performance on two exemplary days

Table 4. HelioTrough performance parameters resulting from dynamic data analysis of data collected at Kramer Junction demonstration loop.

Performance Parameter	value	uncertainty k=2 95% confidence	units
Optical efficiency	0.816	$\pm 0.037$	—
Heat loss $c_1$	0.0622	$\pm 0.0037$	W/(m <sup>2</sup> K)
Heat loss $c_2$	0.00023	$\pm 2.28 \cdot 10^{-5}$	W/(m <sup>2</sup> K <sup>2</sup> )
Capacity $c_5$	2653	$\pm 504$	J/(m <sup>2</sup> K)
IAM $a_1$	$-1.59 \cdot 10^{-3}$	$\pm 5.1 \cdot 10^{-5}$	1/°
IAM $a_2$	$9.77 \cdot 10^{-5}$	$\pm 8.8 \cdot 10^{-7}$	(1/°) <sup>2</sup>

The dynamic analysis yields all performance parameters simultaneously. The moderate parameter uncertainties are mainly due to systematic effects in the uncertainty budgets of irradiance and useful heat. As listed in Table 3 and Table 4 almost identical IAM parameters are obtained from steady-state and dynamic data analysis and thus the IAM curve presented in Figure 3 applies to both analyses. Introducing the result into Equation 3 for a typical test operation point ( $\Delta T_m=220\text{K}$ ,  $\theta=20^\circ$  and  $E_b=1000\text{ W/m}^2$ ) produces a specific yield of  $736\text{ W/m}^2$  and an uncertainty of 4.5% (result of probabilistic uncertainty analysis for 95% coverage probability). Extrapolating Equation 3 to reference conditions results in a thermal collector efficiency of  $>75\%$  for the clean collector at  $750\text{ W/m}^2$ ,  $350^\circ\text{C}$  mean fluid temperature and  $25^\circ\text{C}$  ambient temperature. An illustration of the characteristic of the thermal efficiency indicating the respective data base for steady-state and dynamic analysis is included in Figure 5.

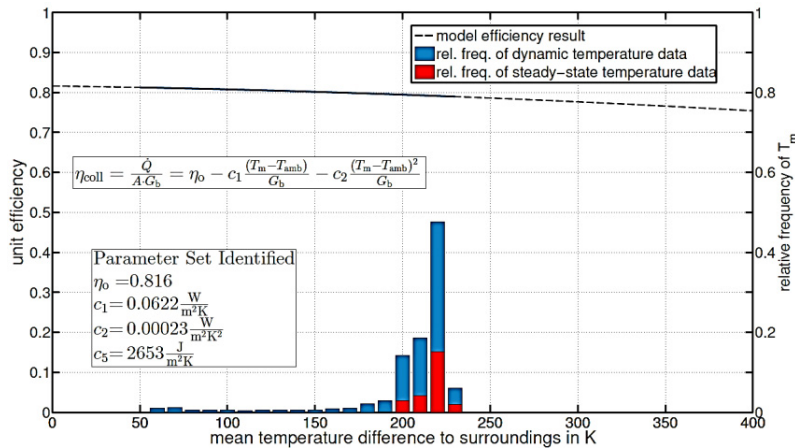


Figure 5. HelioTrough thermal collector efficiency as a function of mean temperature difference to the ambient including an illustration of the respective usable data base for steady-state and dynamic analysis

### 3.3. Observations

Useful collector output data results from a combination of thermal and optical effects are an effective measure of the performance of a parabolic trough system. Typically, testing conditions in the field do not include sufficient operating periods at normal incidence of solar irradiance and broader range of fluid temperatures. This is due to the north-south orientation of the test installations and the solar field control aiming at nominal HTF outlet temperatures. Such field data challenges any kind of data analysis (steady-state or dynamic). As a consequence it is difficult to separate optical and thermal effects and performance parameters are correlated. Nevertheless, a proper set of performance parameters is essential for yield prediction, and it is desirable to obtain or confirm it from full-size operating systems such as a collector or loop.

The above mentioned effects in combination with the classical formulation of collector performance according to the performance equation (eq. 3) give rise to parameter cross-correlation. The predominance of data points at nominal operating temperatures causes a correlation of optical efficiency and thermal loss coefficients as loss mechanisms cannot be separated by the use of a wide temperature range like in small test facilities. Optical efficiency in turn and IAM, both determining the optical input to the system, are also correlated. Consequently, a precondition for the success of the overall parameter identification is the proper identification of the IAM characteristic.

While steady-state data analysis deals with a single operation point in terms of temperature for regular field data, dynamic methods benefit from the temperature range during morning heat-up and night cool down. This facilitates a decoupled identification of parameters and increases the robustness of the parameter identification process. Therefore, for characterization of collectors within solar fields with restricted operation conditions, the latter approach is preferred to steady-state ones which may serve for performance verification according to [1] but not for system characterization. However, the simultaneous identification of all parameters, as opposed to the consecutive



determination in steady-state analysis, still requires data from selected days from a 6-month-period of testing covering a wide range of angles of incidence to reliably determine IAM parameters.

Important result of the comparison of both methods is the good agreement of the parameters obtained from steady-state and dynamic data analysis (Table 3, Table 4), for those parameter for which both provide reliable values. Also the dynamic model and the dynamic performance results agree very well (Figure 4). The temperature range in which results contribute to the analysis is increased from 40 K to 180K. With respect to the method itself, a number of expected effects were observed that led to a refinement of the model and enhancement of the robustness of the optimization. Amongst others, the residual vector is reset in problematic data periods like instrument malfunction (Figure 4) or data gaps.

Data uncertainty – in particular systematic effects – is the decisive factor for resulting values of parameter uncertainty. Furthermore, common practice different weighting of individual data points or days according to the reciprocal values of their absolute uncertainties is not recommended as it typically strengthens periods less relevant for solar field yields such as nights and winter time.

#### 4. Conclusion

The application of the advanced testing and modeling approach (ATM) to the HelioTrough collector testing in the solar field has been successful. The steady-state and dynamic analyses deliver IAM parameters that are in good agreement. In addition the dynamic analysis enables the deduction of a plausible thermal efficiency characteristic from regular field collector performance data. Given a broad distribution of incident angles, performance parameters can be reliably identified from 5-10 sunny testing days. Although partly cloudy days are currently considered less valuable for parameter identification, their useful performance characteristics and yields are still well represented by the parameters and model. The developed model and algorithm for parameter identification by optimization has been refined in view of particular needs of actual field data. In comparison to steady-state evaluation the dynamic method significantly extends the share of useful data in measurements and thus facilitates the evaluation of more relevant performance parameters.

The test evaluation results confirm performance predictions of the design tools as well as the quality of the implementation of the evaluated collector in the demonstration loop in California. The evaluation also serves as verification of FlgSol's steady-state measurements of the past three years and allows good prediction of the HelioTrough performance in future commercial projects.

#### 5. Outlook

The HelioTrough collector development, its tests under commercial field boundary conditions in SEGS-V and the test evaluation have been finalized. With the experience from manufacturing, assembly and operation it is ready for commercial projects.

The advanced testing and modeling approach (ATM) has proven its suitability for field data evaluation. The experience on the qualification of different phases of typical plant operation for parameter identification has been implemented for the upcoming applications. In the next step the ATM method will be applied to evaluate operation data of a whole solar field. This extends the range of test temperatures towards actual operation temperatures of solar fields and the benefits of the dynamic data evaluation are expected to pave the way towards application of the method for acceptance testing of commercial fields as well as faster evaluation of measurement data of test loops of parabolic trough collectors.



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